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EXPERIMENTAL TESTS ON THE EC6 COMPRESSIVE STRENGTH OF MASONRY MADE OF HOLLOW CALCIUM SILICATE UNITS

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Abstract
This paper examines different factors affecting mechanical properties of masonry in compression. Experimental investigations of high precision hollow calcium silicate block masonry with thin layer and general purpose mortar bed joints are presented. Characteristic compressive strength of such masonry determined by experiments was compared with the one which was established by Eurocode 6 [1] method. The analysis of the results of high precision calcium silicate block masonry investigations revealed that the values of the characteristic compressive strength of masonry with thin layer bed joints defined by EC6 method exceed the values determined by experiments made in accordance with EN 1052-1 [21]. According to the results of experimental research, some suggestions are made on how to specify the characteristic compressive strength of masonry which is produced from 1st and 2nd group hollow calcium silicate blocks with thin layer bed joints.

Streszczenie
W artykule analizowano różnego typu czynniki wpływające na właściwości mechaniczne muru ściskanego. Przedstawiono badania doświadczalne murów wykonanych z bloczków silikatowych drążonych o cienkich spoinach warstwowych. Wytrzymałość charakterystyczną na ściskanie takich murów otrzymaną w badaniu porównano z metodą określania wytrzymałości podaną w Eurokodzie 6 [1]. Analiza wyników badań murów wykonanych z bloczków silikatowych wykazała, że wartości charakterystycznej wytrzymałości na ściskanie takich murów określonych zgodnie z metodą podaną w EC6 mogą przekraczać wartości wytrzymałości otrzymane w wyniku badań doświadczalnych wykonanych zgodnie z normą EN 1052-1 [21]. Na podstawie wyników badań eksperymentalnych przedstawiono propozycje określenia charakterystycznej wytrzymałości na ściskanie muru który jest produkowany z 1 i 2 grupy bloków silikatowych drążonych o cienkich spoinach warstwowych.

Keywords: **Hollow Masonry Units; Calcium Silicate; Thin Layer Mortar; Bed Joint Thickness; Characteristic Compressive Strength.**

1. INTRODUCTION

Recently, a range of solutions applied to materials and structures of masonry units has been evolving. One of these solutions is the use of high precision hollow silicate blocks. The application of such units enables reduction of bed joint thickness up to 2-3 mm, without filling perpend joints.

Different scientific research references provide plenty of information on masonry with general purpose masonry mortar bed joints of $3<h_m\leq15$ mm thick. However, not much can be found concerning masonry of high precision calcium silicate masonry units and thin layer joints of $0.5\leq h_m\leq3$ mm.

The characteristic compressive strength of masonry is determined either by experiments or calculated by application of empirical reliance. Eurocode 6 (EC6) [1] framework for masonry structures gives certain recommendations to determine the characteristic compressive strength of masonry by using formulas which assess various factors, affecting the masonry compressive strength, through the application of empirical coefficients. When new materials and new masonry units are used for masonry, it is essential to verify the method for determining mechanical masonry property – compressive strength – as provided under the EC6 [1].

The compressive strength of masonry depends on the following factors: compressive strength of masonry units, their material type and form, thickness and strength of mortar in bed joints, quality of masonry, etc [2]. Various experimental investigations [3-7] show that the compressive strength of masonry mostly depends on the strength of masonry units and on the ratio between bed joint mortar and the strength of masonry units. The increment in the compressive strength of masonry mainly depends on the strength of masonry units, their type and material.

Experimental investigations [4] on varying strength of masonry units and of mortar strength reveal that the greatest influence of a unit strength on masonry strength is in the case of weaker mortar use. The compressive strength of masonry greatly depends on the strength of mortar. The compressive strength of masonry increases along with the enhancement of the strength of mortar. Mortar effect varies according to a type of a masonry unit. *R.G. Drysdale's* investigations [6] on concrete block masonry revealed a linear relationship between the compressive strength of masonry and mortar strength.

Mortar in bed joints affects not only the compressive strength of masonry but also behaviour of masonry. The increase in mortar compressive strength results in the reduction of masonry ultimate strain. Masonry becomes both stronger and more brittle. Some authors [4, 7] do not recommend the application of high strength mortar for masonry because of the side effect.

As it was mentioned before, the compressive strength of masonry depends on a kind of a unit used (type of material, form of units). *Chanine's* [5] research on hollow concrete block masonry shows a linear relationship between the compressive strength of masonry and the strength of masonry units. It also reveals that this relationship differs from the relationships obtained by other scientists [3, 4].

Since masonry units are subjected to tension due to their interaction with bed joints, tensile strength of masonry units becomes a very important property. Horizontal tensile stresses in a masonry unit are resisted by a vertical section of a masonry unit. This is the reason why masonry strength is significantly affected by a vertical section of masonry units, which in turn depends on geometry of a unit (height of a masonry unit, amount of holes and arrangement character of holes). The value of horizontal tensile stresses in a unit depends not only on a unit itself but also on the thickness of mortar joint as well as quantity of bed joints. The quantity of bed joints can be defined by a ratio of h_m/h_u (here: h_u and h_m – height of a unit and mortar in a bed joint respectively). This ratio defines the influence of a mortar joint thickness.

The increase in a masonry unit height results in the increase of a unit vertical section area as well as of a load bearing capacity of vertical section of masonry units. It could be stated that the compressive strength of masonry reduces in case of the increase in the thickness of a mortar joint when the height of a unit is constant [8]. This was confirmed by a number of performed investigations [9]. The resuts of investigations shows the influence of the mortar joint thickness on the compressive strength of a solid cross-section and of hollow ceramic brick masonry. The investigations point out that for the same mortar strength, the increase in the bed joint thickness from 1 mm to 25 mm resulted in the reduction of the compressive strength of solid brick masonry by 42%, whereas the compressive strength of hollow brick masonry decreased by 80%. Investigations conducted by *Hendry* [8] say that the change in mortar joint thickness has a more significant effect on the strength of masonry made of low (lower height) masonry units (bricks) than on the strength of block (higher masonry units) masonry. The latter is explained by a very small value of joint thickness to a block height ratio h_m/h_u. Results of block masonry investigations [6] revealed that joint thickness influences the strength of masonry made of blocks.

The compressive strength of masonry greatly depends on holes in masonry units. The area of a masonry vertical section is reduced due to holes in units, which in turn results in reduction of a compressive strength of masonry [9]. The compressive strength of hollow brick masonry, in comparison with a solid brick masonry (mortar joint thickness varied from 5 up to 25 mm), decreases from 17 to 65% [9]. Tests with calcium silicate hollow block masonry performed by authors of this paper [10, 11] showed that in such masonry units the first vertical cracks mostly

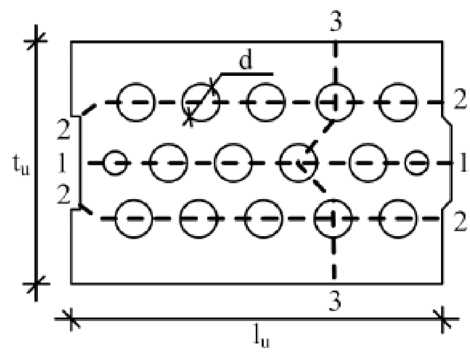

Figure 1.
Possible vertical sections of hollow unit failure: (1 – 1), (2 – 2), (3 – 3)

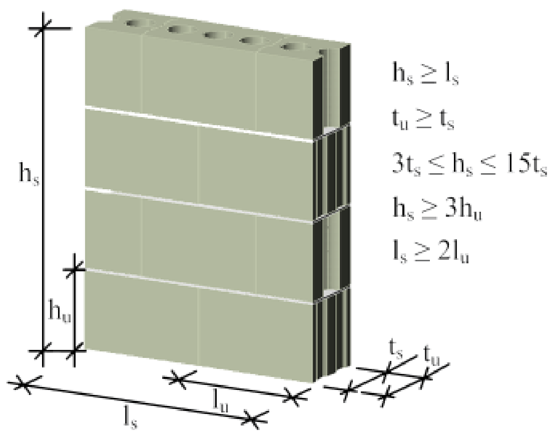

Figure 2.
Specified limits of dimensions for specimens used in masonry tests in accordance with EN 1052-1 [21]

appear in the weakest section. The greatest load bearing capacity of a vertical section is proportional to a ratio of l_n/l. Here: $l_n=l-\Sigma d$ (l – width of a masonry unit t_u or its length l_u; d – hole diameter Fig. 1. Load bearing capacity of vertical section increases with a ratio of l_n/l. Authors [10] distinguish an additional factor enabling to affect the compressive strength of masonry made of hollow masonry units. In most cases, block holes take conical shape. Therefore, mortar in a hole can possibly make a wedge. During a load action, mortar in a hole of a masonry unit puts pressure on walls of a hole and imposes additional horizontal tensile stresses and strains in a block. These additional tensile forces reduce the strength of a masonry unit vertical section.

2. THE DESCRIPTION OF AN EXPERIMENTAL INVESTIGATION

Most of experimental investigations are performed on masonry made of various types of bricks and ceramic or concrete blocks, as well as bed joints of general purpose mortar [12-18]. There is little data available about experimental investigations on mechanical properties of masonry made of high precision hollow calcium silicate blocks [19, 20, 35].

Extensive investigations seeking to examine the impact of various factors on properties of masonry in compression made of hollow high precision calcium silicate masonry units with not filled vertical joints have been carried out at *Vilnius Gediminas Technical University.*

The investigations examined the influence on the compressive strength of masonry made of calcium silicate masonry units of the following factors: strength and hollowness of masonry units, bed joint thickness and mortar strength, moistening of masonry units when thin layer mortar is used.

Masonry specimens conforming EN 1052-1 [21] were tested by a short-term load, see Fig. 2. Hollow calcium silicate masonry units of various types (they differ in geometry and strength class) were used for specimens and are shown in Table 1 and Fig. 3. Specimens were made in laboratory by a bricklayer of high category, i.e. the quality of the work was nearly the same as at the construction site. The specimens were made placing mortar on the whole bed surface of a unit evenly using "comb" type spreader. For the specimens, a thin layer mortar was used when a bed joint

Table 1.
Geometrical and mechanical data of masonry units used in the investigations

No.	Unit name	Unit dimensions [mm]			Unit's ratio of hollows [%]	Compressive strength f_b [N/mm^2]	Unit class
		length	width	height			
1	SB 120	250	120	238	18	15.9; 27.2	15; 25
2	SB 248		250		25.4	11.4; 17.6; 23.5	10; 17.5; 20
4	M15		150		13.9	22.1	20
5	M18	340	180	198	27.2	17.1; 17.8	15; 17.5
6	M25		250		22.6	16.7; 18.9	15; 17.5

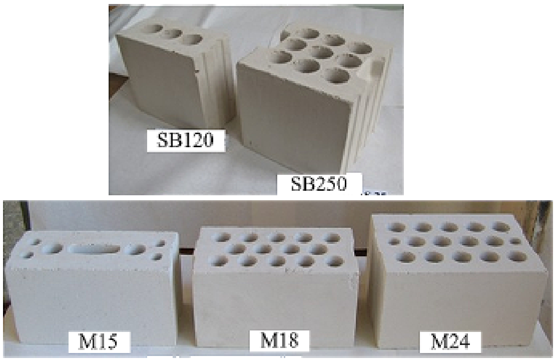

Figure 3.
High precision hollow calcium silicate masonry units used in the tests

thickness was up to 3 mm, and general purpose mortar was used for bed joints of 3 mm<h_m≤15 mm thick. According to cone penetration, a mortar slump during placing was 110-130 mm and a mortar strength varied from 3.5 N/mm^2 to 23.5 N/mm^2. Specimens were subdivided into series, where one series consisted of 3 specimens. 75 specimens were produced and tested. The strength of units of each lot was determined according to the requirements imposed by the standard EN 772-1 [22]. During execution, mortar control samples were made for each series of masonry specimens and tested in conformity with the standard EN 1015-1 [23].

The results of the tests are presented in Figures 4-6. The influence of various factors on masonry in compression mechanical properties can be evaluated by the utilization level of masonry units' compressive strength, i.e. by the ratio between normalized compressive strength of masonry units fb and the compressive strength of masonry $f_{k.obs}$, (f_b/ $f_{k.obs}$.). Ratio f_b/ $f_{k.obs}$ indicates the utilization level of the compressive strength of masonry units. When the compressive strength of masonry units is completely utilized, this ratio equals one.

Figures 4, 5 illustrate the relationships between the compressive strength of masonry and mortar strength in a case of thin layer mortar (thin joints, h_m≤3 mm) and of general purpose mortar (thick joints, 3 mm<h_m≤15 mm).

Fig. 4 shows that as mortar compressive strength is increased, the utilization level of the compressive strength of masonry units is reduced. The investigations revealed that the utilization level of masonry units' strength depends on bed joint thickness and on the compressive strength of mortar Figs. 4, 5. When the compressive strength value of mortar in bed

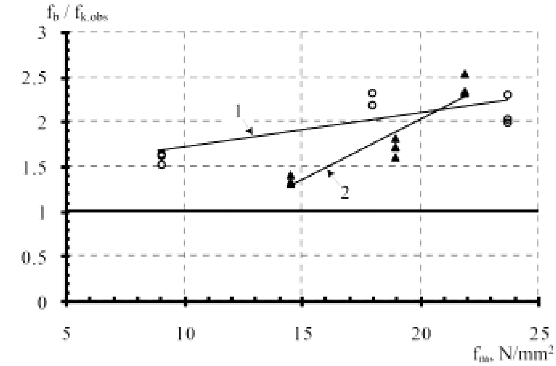

Figure 4.
The dependence of the relationship between the compressive strength of calcium silicate masonry units f_b and the compressive strength of masonry $f_{k.obs}$ on mortar compressive strength f_m (1 – masonry with thick joints, 2 – masonry with thin layer mortar)

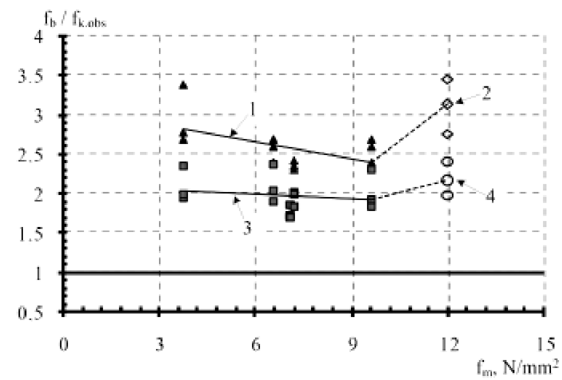

Figure 5.
The dependence of the relationship between calcium silicate masonry unit's compressive strength f_b and masonry compressive strength $f_{k.obs}$ ratio on compressive strength of masonry f_m (1 and 3 – respectively, moistened when laying calcium silicate blocks M18 and M25; 2 and 4 – respectively, not moistened calcium silicate blocks M18 and M25)

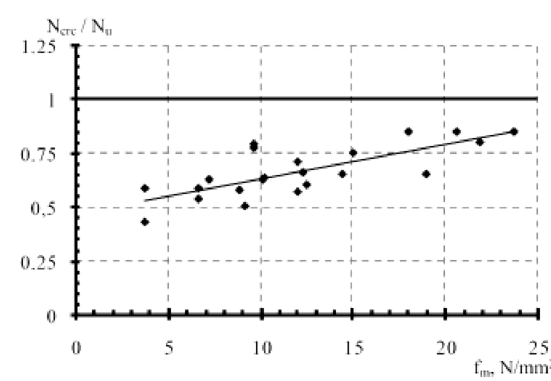

Figure 6.
The dependence of the relationship between ratio of cracking load N_{crc} and the ultimate load N_u on the compressive strength of mortar f_m

joints is greater (15-25 N/mm^2) and we increase mortar compressive strength from 15 N/mm^2 to 25 N/mm^2, the utilization of the compressive strength of masonry units is more efficient using common thickness of bed joints (h_m= 8-12 mm) than thin layer joins (h_m≤ 3 mm) Fig. 4. In the case of low strength mortar (up to 15 N/mm^2), the influence of a mortar strength variation on utilization level of masonry units (ratio f_b/f_{obs}) is not significant Fig. 4. It might be due to stress concentration in bed joints. The use of lower strength mortar or thicker bed joints predetermines lower concentration of stresses across a joint, i.e. in both cases, the distribution of stresses across a bed joint is more uniform.

The concentration of stresses across a bed join may also be influenced by the zone formed in the interface of a masonry unit and a bed joint, in which the compressive strength of masonry can be lower. This is due to masonry unit's excessive water absorption from a bed joint mortar [10, 24-26]. It is of great importance for thin layer mortar (when joints are thin). The diagram below, curves 2 and 4 in Fig. 5, illustrates an additional effect of moistening on the compressive strength of masonry when laying blocks. The diagram Fig. 5 indicates that the utilization of not moistened masonry units is 10-25% less than that of masonry units which where moistened when laying them. Geometrical parameters (hollowness and arrangement of webs) are of great effect on the compressive strength of masonry. In the diagram Fig. 5, the relationships between the compressive strength of masonry and mortar strength for masonry units of different hollowness ratio – calcium silicate blocks M18 see Fig. 5, curves 1, 2 and M25 Fig. 5, curves 3, 4 are presented. Hollowness ratio of blocks M18 is greater than M25 see Table 2. This feature determines lower strength of vertical section. Furthermore, it is observed that the utilization level of the compressive strength within calcium silicate blocks M25 curves 3 and 4 in Fig. 5 is approximately 35% higher than the one for blocks M18.

The experimental investigations carried out by authors of the present article and other scientists reveal that the compressive strength of masonry is enhanced by increasing the compressive strength of mortar [4]. However, the increase in the compressive strength of mortar also causes the change of masonry failure mode [20]. Masonry becomes more stiff and brittle. The first cracks appear under condition of greater stress. Meanwhile, when using high-strength mortars, cracking load values approach to a failure load (masonry fails immediately after appearance of the first crack). This is illustrated by the relationship presented in Fig. 6. It is shown that relative bearing load capacity N_{crc}/N_u approaches to one (here N_{crc} – load as the first crack appears and N_u – maximum load sustained by specimen), as the compressive strength of mortar increases.

3. THE CALCULATION OF COMPRESSION STRENGTH OF MASONRY IN ACCORDANCE WITH EC6

The investigations reveal that the compressive strength of masonry depends on different factors such as the strength of masonry units, form of masonry units, thickness of bed joints, mortar strength, quality of masonry, etc. Therefore, it is difficult to present universal mathematical formula for the determination of the compressive strength of masonry, taking into account all the factors which influence mechanical properties of masonry. In literature, there have been various methods for the calculation of masonry strength presented by *Hilsdorf* [27], *Francis* [9], *Ohler* [28], described in [29]. They evaluate many side factors; however, accuracy in calculation results can be achieved not in all the cases [30-32]. For the calculation of the compression strength of masonry, mostly empirical relationship between the compressive strength of masonry and the compressive strength of masonry units and mortar are applied. The influence of form of masonry units (dimensions, hollowness), types of materials and thickness of bed joints on the compressive strength of masonry is taken into account by empirical coefficients.

A general description of masonry characteristic compressive strength can be made by the following function:

$$f_k = F(f, f_m, h_m, K), \tag{1}$$

where: K – empirical coefficient evaluating a type of a masonry unit, hollowness, a type of material and other factors; f and f_m – compressive strengths of masonry units and mortar respectively; h_m – thickness of a bed joint.

The code for design of masonry structures EC6 [1] recommends to determine characteristic compressive strength of masonry from tests on masonry specimens in accordance with the code EN 1052-1 [21]. In this case, the characteristic strength of masonry f_k is determined by taking the lower value of:

$$f_k \leq \left| \begin{matrix} f_{vid}/1{,}2 \\ f_{\min} \end{matrix} \right., \qquad (2)$$

here: f_{vid} – the mean value of compressive strength of masonry specimen; f_{min} – the lowest value of compressive strength for individual specimen. The determination of compressive strength by tests is time and labour consuming. Therefore, it is expedient to use it when new masonry units (new by structure or material) or new solutions of masonry structures are applied [31-34].

In other cases, the characteristic compressive strength of masonry f_k can be determined in accordance with EC6 [1], using empirical formula which has a following general expression:

$$f_k = K \cdot f_b^{\alpha} \cdot f_m^{\beta}, \qquad (3)$$

here: f_b – normalized compressive strength of a masonry unit (masonry unit class is associated with this strength); f_m –the mean compressive strength of mortar (compressive strength class); K – coefficient evaluating factors mentioned above (see formula 1); α and β – empirical indexes evaluating influence of a type (kind) of mortar and thickness of a bed joint h_m.

The values of coefficients (indexes) α and β are presented in Table 2. In the case of thin layer mortar (for thin joints of), $\beta = 0$, i.e. it means that mortar compressive strength is considered to be insignificant for compressive strength of masonry with thin joints.

Formula (3) shows that the compressive strength of masonry units is of the greatest influence on the compressive strength of masonry.

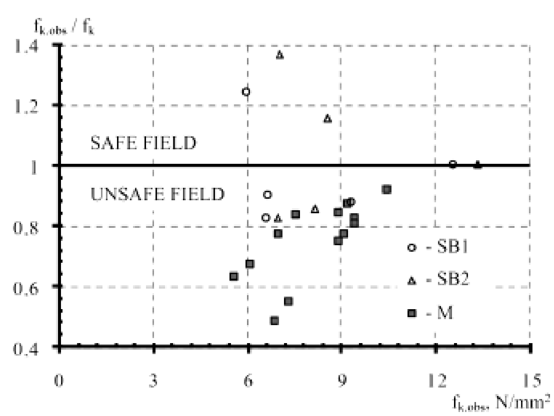

Figure 7.
The variation of experimental to theoretical characteristic masonry strength values $f_{k.obs}$ / f_k ratio with experimental characteristic masonry strength value $f_{k,obs}$

The increase of masonry strength is accelerated more by the enhancement of the compressive strength of masonry units than of mortar strength. As the compressive strength of masonry units is increased two times (from 10 N/mm^2 to 20 N/mm^2), the compressive strength of masonry increases by 63%. Meanwhile, the double increase (from 10 N/mm^2 to 20 N/mm^2) in mortar strength, results in the enhancement of compressive masonry strength by 23%. According to the formula (3) of EC6 [1], the dependence of the compressive strength of masonry on the compressive strength of units and mortar is almost linear.

The relationship (3) is based on experimental investigations. However, when new materials and new shapes of masonry units are applied, formula (3) does not always give accurate values of the masonry compressive strength. In some cases, the characteristic value of the compressive strength of masonry f_k, which is determined by the relationship (3), is substantially greater than the characteristic value of the masonry compressive strength $f_{k.obs}$ obtained by

Table 2.
Values of coefficients α and β

Mortar type	Value
General purpose mortar	α=0.7 β=0,3
Lightweight mortar	α=0.7 β=0,3
Masonry with thin layer bed joints (h_m≤3 mm) silicate, aggregate concrete, autoclaved aerated concrete masonry units and ceramic masonry units of 1 and 4	α=0.85 β=0
Masonry with thin layer bed joints (h_m≤3 mm) and ceramic masonry units of 2 and 3	α=0.7 β=0

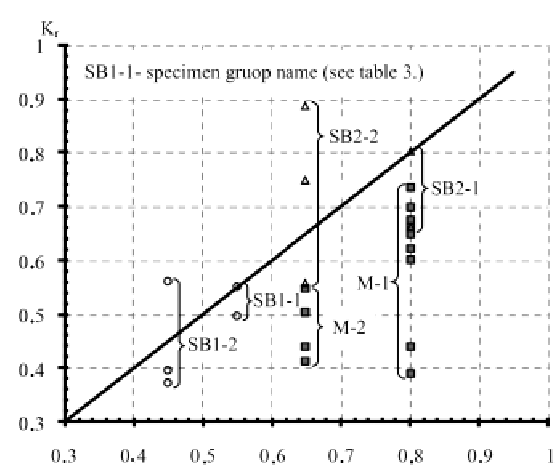

Figure 8.
The values of empirical coefficients *K*, determined in accordance with EC6, and K_r obtained from experiments

Table 3.
The description of specimens groups

Name of specimens group	Number of specimens	Mortar type	Masonry units applied	Group of masonry units (accord. EC6)	Mean of ratio $f_{k.obs}/f_k$	c.o.v
SB1-1	2[a] (6[b])	General purpose mortar h_m=8-12 mm	SB120	1	1.04	0.213
SB1-2	3[a] (9[b])		SB248	2		
SB2-1	2[a] (6[b])	Thin layer mortar $h_m \leq 3$ mm	SB120	1	0.97	0.171
SB2-2	3[a] (9[b])		SB248	2		
M-1	10[a] (30[b])	Thin layer mortar $h_m \leq 3$ mm	M15, M25	1	0.76	0.159
M-2	5[a] (15[b])		M18	2		

a – number of series in group
b –total number of specimens in group

experimental investigations. Using their experiments, the authors of this article determined characteristic values of the compressive strength of masonry made of high precision hollow calcium silicate blocks fk.obs and compared them with characteristic values f_k obtained from formula (3). Fig. 7 presents the variation of ratio between characteristic compressive strength value, determined by tests $f_{k.obs}$, and value f_k, calculated by using formula (3). Table 3 shows the variation coefficient of the mean value of the ratio. The analysis of data in Fig. 7 and Table 3 reveals that in many cases characteristic values of the compressive strength of masonry calculated using formula (3) exceed the values determined by experiments, see Fig. 7. Similar results were obtained by other investigators [16, 35] when testing ceramic and calcium silicate block masonry. Data presented in Fig. 7 and Table 3, show that the most significant difference between characteristic values of the compressive strength of masonry, obtained by calculations using formula (3) and experiments, is for masonry specimens with thin layer mortar (with thin bed joints), which were produced without additional moistening of masonry units (blocks) or when weaker thin layer mortar was used. In the calculation of the compressive strength for thin layer masonry in accordance with EC6 [1], the compressive strength of mortar does not have any influence. However, after the analysis of experimental investigation results, it can be assumed that the compressive strength of masonry depends on the strength of mortar. Data presented in Fig. 7 and Table 3, show that the compressive strength of masonry made of hollow calcium silicate blocks of the first and the second groups with thin layer mortar bed joints determined by the calculation which is in accordance with EC6 [1] methods (by formula (3) is substantially too high. Therefore, reliability of the calculation method is reduced and needs correction. In the calculation of the characteristic compressive strength of masonry, the influence of various factors (structure of masonry units, type of a unit's material, etc.) is evaluated by coefficient K. The values of required empirical coefficient K_r, determined by the results of experimental investigations which were carried out by authors of this paper, are presented in Fig. 8. Fig. 8 suggests that values of K, in the case of masonry made of hollow calcium silicate blocks of the first and the second groups with thin layer mortar bed joints, should be taken lower than the ones given in the Eurocode EC6 [1].

According to the results of experimental research it is offered to calculate the characteristic compressive strength of masonry which is produced from 1st and 2nd group hollow calcium silicate blocks with thin layer mortar bed joints using reduced empirical coefficient K. It could be reduced multiplying its value by correction coefficient depending on mortar strength β_K. According to the results of experimental research the coefficient $\beta_K = 1$ when thin layer mortar strength $10 \leq f_m \leq 20$ N/mm^2, and $\beta_K = 0.75$ when $f_m < 10$ N/mm^2.

4. CONCLUSIONS

Mortar in bed joints has an influence not only on the compressive strength of masonry but also on the behaviour of masonry. As the strength of mortar is increased, ultimate strains of masonry are reduced and, consequently, masonry becomes both stronger and more brittle. In the presence of greater stresses in masonry, the first cracks appear, whereas the use of high strength mortar is a cause of the failure of masonry, which comes up after the first cracks, see Fig. 6.

The compressive strength of masonry from high precision hollow blocks depends on the compressive strength of both masonry units and thin layer mortar in bed joints.

The value of characteristic compressive strength of masonry from high precision hollow calcium silicate blocks, which was calculated using the method of EC6 [1], substantially exceeds the compressive strength of masonry determined by tests.

In order to calculate the characteristic compressive strength of masonry made of high precision calcium silicate blocks with thin layer mortar, it is recommended to use reduced empirical coefficient K, i.e. to multiply its value by coefficient β_K. According to results of experimental research of masonry which is produced from 1st and 2nd group hollow calcium silicate blocks with thin layer bed joints coefficient β_K depends on the compressive strength of mortar and it can be used as follows: $\beta_K = 1$ when $10 \leq f_m \leq 20$ N/mm^2 and $\beta_K = 0.75$ when $f_m < 10$ N/mm^2. Although the reduced value of coefficient K could be evaluated in the Lithuanian National Annex of EC6 without considering correction coefficient β_K.

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